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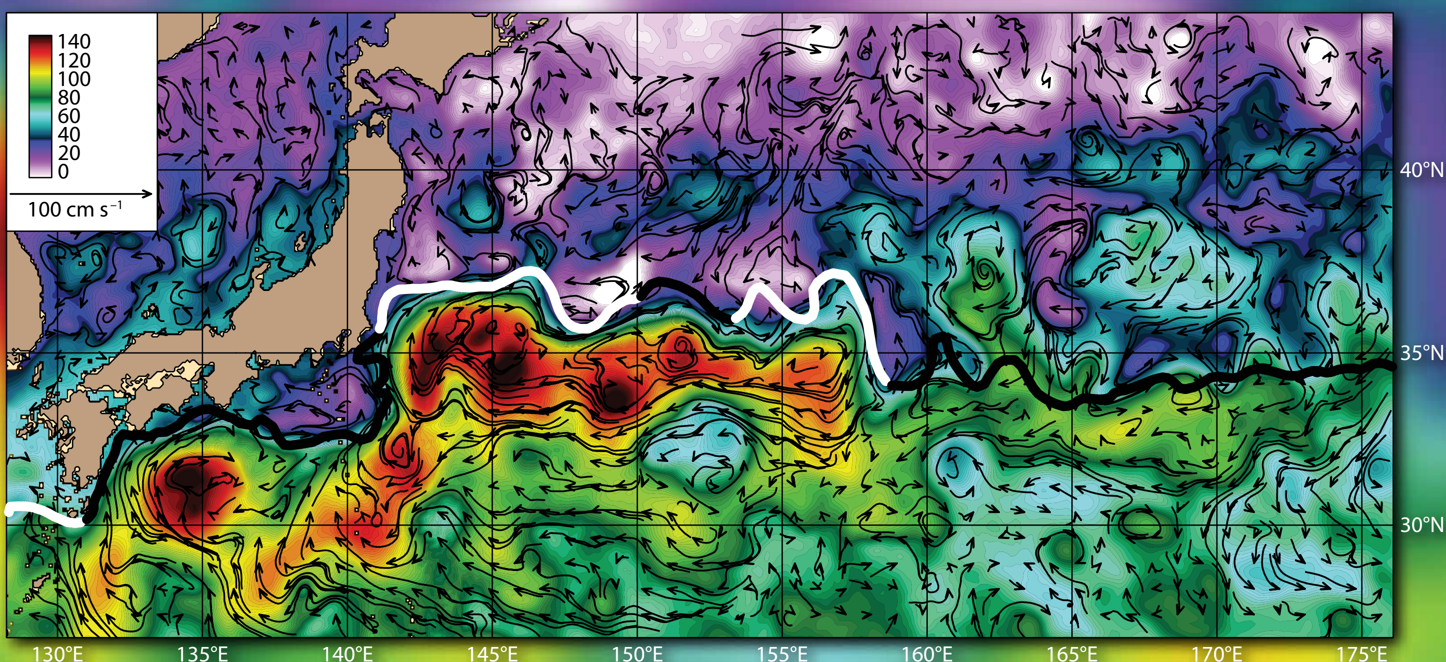
US Navy Operational Global Ocean and Arctic Ice Prediction Systems

BY E. JOSEPH METZGER, OLE MARTIN SMEDSTAD, PRASAD G. THOPPIL, HARLEY E. HURLBURT, JAMES A. CUMMINGS, ALAN J. WALLCRAFT, LUIS ZAMUDIO, DEBORAH S. FRANKLIN, PAMELA G. POSEY, MICHAEL W. PHELPS, PATRICK J. HOGAN, FRANK L. BUB, AND CHRIS J. DeHAAN



An example from the operational Global Ocean Forecast System that shows the proper placement of the Kuroshio (the strongly inertial western boundary current in the North Pacific Ocean) relative to an independent infrared sea surface temperature analysis (black/white line), and current vectors that highlight the mesoscale eddy field.

ABSTRACT. The US Navy's operational global ocean nowcast/forecast system is presently comprised of the 0.08° HYbrid Coordinate Ocean Model (HYCOM) and the Navy Coupled Ocean Data Assimilation (NCODA). Its high horizontal resolution and adaptive vertical coordinate system make it capable of producing nowcasts (current state) and forecasts of oceanic "weather," which includes three-dimensional ocean temperature, salinity, and current structure; surface mixed layer depth; and the location of mesoscale features such as eddies, meandering currents, and fronts. It runs daily at the Naval Oceanographic Office and provides seven-day forecasts that support fleet operations, provide boundary conditions to higher resolution regional models, and are available to the community. Using a data-assimilative hindcast and series of 14-day forecasts for 2012, the system is shown to have forecast skill of the oceanic mesoscale out to about 10 days for the Gulf Stream region and to 14+ days for the global ocean and other selected subregions. Forecast skill is sensitive to the type of atmospheric forcing (i.e., operational vs. analysis quality). Subsurface temperature bias is small (< 0.25°C) and root mean square error peaks at the depth range of the mixed layer and thermocline. Coupled to the Community Ice CodE (CICE) on the same grid, the HYCOM/CICE/NCODA system (initially restricted to the Arctic) provides sea ice nowcasts and forecasts. Ice edge location errors are improved from the previous sea ice prediction system but are limited in part by the accuracy of the satellite observations it assimilates.

INTRODUCTION

Development of an advanced eddy-resolving global ocean nowcasting/forecasting system has long been a topic of US Navy interest (Anonymous, 1976; Ocean Prediction Workshop, 1986). Rhodes et al. (2002) documented the status of Navy efforts toward this goal over a decade ago, and this article describes the current state of Navy global operational ocean prediction. This system provides nowcasting and forecasting of oceanic "weather," including three dimensional (3D) ocean temperature, salinity, and current structure; surface mixed layer depth; and the location of mesoscale features such as eddies, meandering currents, and fronts. The spatial scales of the eddies range from 50 km to 500 km, and the meandering currents are typically about 100 km wide, with speeds exceeding 1 m s^{-1} in the western boundary current regions of the Gulf Stream (Atlantic), the Kuroshio (Pacific), and the Agulhas and Somali Currents (both Indian). Consequently, numerical ocean models with ~ 10 km or finer horizontal resolution and, depending on the vertical coordinate design, ~ 30 or more vertical coordinate surfaces are needed to resolve the surface boundary layer, coastal regions, and thermocline, and thus depict the 3D ocean structure with accuracy superior to climatology and/or persistence (i.e., a forecast of no change). The horizontal resolution must be adequate for the model to generate strong inertial currents and flow instabilities that generate mesoscale eddies and current meanders. Due to the highly nonlinear nature of these flow instabilities (i.e., small initial errors can grow rapidly), sophisticated data assimilation techniques must be employed to constrain the oceanic mesoscale with observations, but they must also be affordable within the constraints of an operational computing environment.

The multinational Global Ocean Data Assimilation Experiment (GODAE; Smith, 2000, 2006) began in 1997 with the goal of fostering development of eddy-resolving global ocean prediction systems in several participating countries (Australia, Britain, France, Japan, and the United States). A good summary of the GODAE systems can be found in Dombrowsky et al. (2009) and Hurlburt et al. (2009). The US effort consisted of a broad partnership of institutions (from government, academia, and business) funded by the National Ocean Partnership Program (Chassignet et al., 2009). Prediction systems were ultimately transitioned for operational use by the US Navy at the Naval Oceanographic Office (NAVOCEANO), covering the entire globe, and by the National Oceanic and Atmospheric Administration at the National Centers for Environmental Prediction (NCEP), initially for the North Atlantic (Mehra and Rivin, 2010) and later for the entire globe. These systems use the community-developed HYbrid Coordinate Ocean Model (HYCOM) as their model component. HYCOM is unique in that it allows a truly general vertical coordinate, which extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in

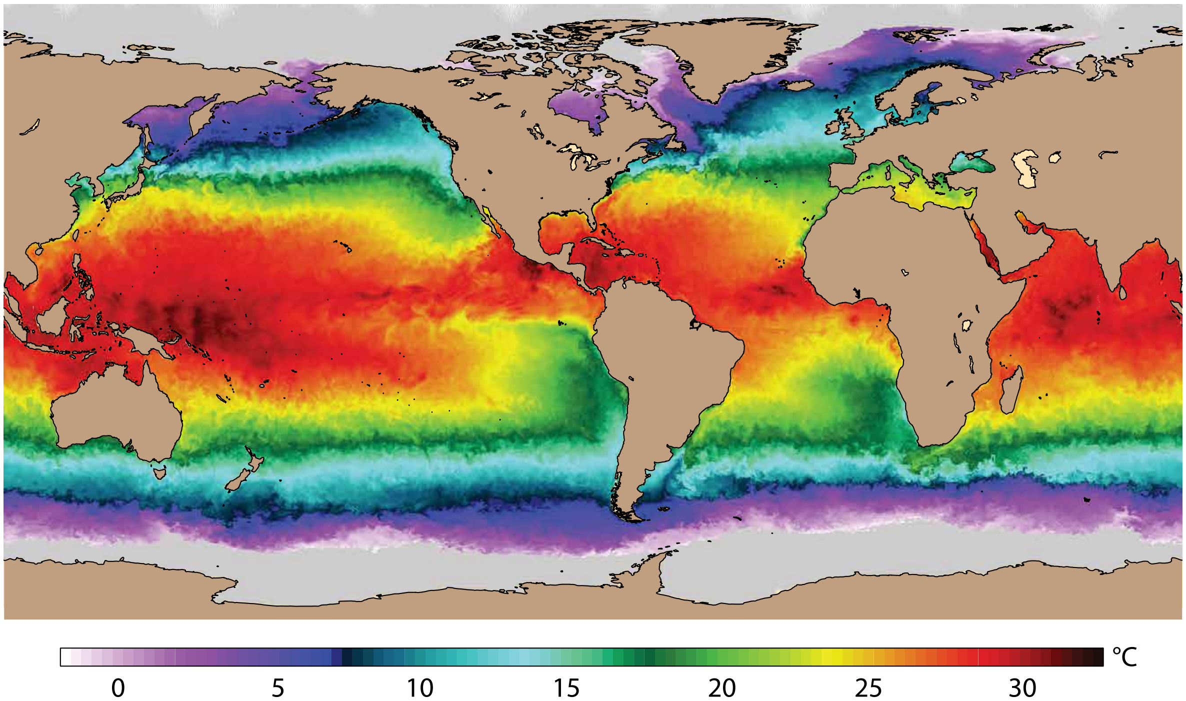


Figure 1. Sea surface temperature (°C) for November 3, 2013, 00Z from the operational Global Ocean Forecast System using NAVy Global Environmental Model (NAVGEM) atmospheric forcing and run daily at the Naval Oceanographic Office (NAVOCEANO). The gray areas in the polar latitudes are sea ice.

stratified regions, while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics (Chassignet et al., 2007).

From the Navy's perspective, knowledge of the ocean environment has many applications, some of which include boundary data for regional/coastal models, tactical planning, optimum-track ship routing, search and rescue operations, long-range weather prediction, and locating high current shear zones. The Naval Research Laboratory (NRL) developed a system to address these needs, validated it against a variety of observations (Metzger et al., 2008, 2010), and delivered it to NAVOCEANO as the Global Ocean Forecast System 3.0 (GOFS 3.0). This system uses global HYCOM and Navy Coupled Ocean Data Assimilation (NCODA) (Cummings and Smedstad, 2013), hereafter referred to as HYCOM/NCODA. The world's first real-time eddy-resolving global system with high vertical resolution, it has been running daily since February 16, 2007. It was declared operational on March 20, 2013, and joined the French Mercator system (http://www.mercator-ocean.fr; Lellouche et al., 2013) and the NCEP Global Real-Time Ocean Forecast System (http://polar.ncep.noaa.gov/global) as operational eddy-resolving global ocean prediction systems, the latter using the Navy's global ocean application of HYCOM. Each day, the Navy system produces a seven-day forecast with graphical output available from NRL (http://www7320.nrlssc.navy.mil/GLBhycom1-12) and numerical output posted on the HYCOM consortium server (http://www.hycom.org/ocean-prediction). Figure 1 shows an example of instantaneous sea surface temperature (SST) for November 3, 2013, at 00Z. A tropical instability wave can be seen in the eastern equatorial Pacific Ocean, and the black ribbon of color in the Southern Hemisphere represents the northern edge of the Antarctic Circumpolar Current.

The ice environment in the Arctic Ocean is also important for strategic and economic reasons. Navy interest in the region has always been high but has grown over the past decade because of the diminishing trend in year-to-year sea ice extent and thickness (National Snow and Ice Data Center, 2013). The occasional seasonal navigability of both the Northwest Passage and the Northern Sea Route brings increased military and commercial maritime operations to a region that previously had limited activity. Thus, a new sea ice prediction system that focuses on the Arctic was developed to provide forecasts of the rapidly changing ice environment.

GLOBAL HYCOM

Global HYCOM has an equatorial horizontal resolution of 0.08° (1/12.5° or ~ 9 km near the equator, ~ 7 km at mid-latitudes, and ~ 3.5 km near the North Pole), which makes it eddy-resolving for the mesoscale, that is, it can resolve the dynamics required to directly simulate western boundary currents, mesoscale variability, and the position and sharpness of ocean fronts. In particular, an eddy-resolving ocean model is required to resolve the physics of baroclinic instability, which means it must (a) resolve the first baroclinic Rossby radius of deformation because of its relation to the predominant spatial scale for baroclinic instability, (b) be able to simulate strong, baroclinically unstable inertial jets (and associated recirculation gyres) that penetrate far into the ocean interior, and (c) resolve the physics of baroclinic instability very well in order to transfer sufficient energy into the abyssal layer (Hurlburt et al., 2009, 2011). Upper ocean–topographic coupling occurs when flow instabilities drive abyssal currents that in turn steer the pathways of upper ocean currents. In ocean prediction, this coupling is important for ocean model dynamical interpolation skill in data assimilation/nowcasting and in ocean forecasting, which is feasible on time scales up to about a month (Hurlburt et al., 2008). Models that generate eddies and current meanders but do not meet the preceding criteria are termed eddy-permitting, and are less effective dynamical interpolators in data-assimilative ocean forecast systems.

The HYCOM grid is uniform cylindrical from 78.64°–66°S and a Mercator projection from 66°S to 47°N. North of 47°N, it employs an Arctic dipole grid, with the poles shifted over land to avoid a singularity at the North Pole (Murray, 1996). This version employs 32 hybrid vertical coordinate surfaces with potential density referenced to 2,000 m and includes the effects of thermobaricity (i.e., the modulation of seawater compressibility by potential temperature anomalies) (Chassignet et al., 2003). Vertical coordinates can be (1) isopycnals (density tracking), often best in the deep stratified ocean; (2) levels of equal pressure (nearly fixed depths), best used in the mixed layer and unstratified ocean; and (3) sigma levels (terrain-following), often the best choice in shallow water. HYCOM combines all three approaches by choosing the optimal distribution at every time step. The model makes a dynamically smooth transition between coordinate types by using a layered formulation of the continuity equation. HYCOM is configured with options for a variety of mixed layer submodels (Halliwell, 2004), and this version uses the K-Profile Parameterization. A more complete description of HYCOM physics can be found in Bleck (2002). A thermodynamic "energy-loan" ice model within HYCOM is a component of the global system discussed here. It allows ice to grow/melt in response to changes in temperature or heat fluxes, but the ice is not advected by the wind or ocean currents. It has less sophisticated dynamics than the ice model used in the Arctic forecast system discussed below.

The ocean model uses atmospheric forcing from the Fleet Numerical Meteorology and Oceanography Center. The output is available at three-hour intervals and initially came from the Navy Operational Global Atmospheric Prediction System (NOGAPS), but changed to the NAVy Global Environmental Model (NAVGEM) in August 2013.

NCODA

The version of NCODA presently used is a fully 3D, multivariate, variational ocean data assimilation scheme. The 3D ocean analysis variables include temperature, salinity, geopotential, and the vector velocity components, all of which are analyzed simultaneously. NCODA can be run in stand-alone mode, but here it is cycled with HYCOM to provide updated initial conditions for

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the next model forecast in a sequential incremental update cycle. Corrections to the HYCOM forecast are based on all observations that have become available since the last analysis. These include surface observations from satellites, such as altimeter sea surface height (SSH) anomalies, SST, and sea ice concentration, plus in situ SST observations from ships and buoys as well as temperature and salinity profile data from XBTs (expendable bathythermographs), CTDs (conductivity-temperature-depth sensors), gliders, and Argo floats. See Table 13.1 in Cummings and Smedstad (2013) for a more complete list, although new observational data types are routinely added. By combining these various observational data types via data assimilation and using the dynamical interpolation skill of the model, the 3D ocean environment can be more accurately nowcast and forecast.

Because of the relative wealth of surface observations in comparison to subsurface observations, an important aspect of any data assimilation methodology is the ability to project surface observations downward to perform the 3D ocean analysis. For single level observations, such as SST, this is done using vertical correlations where length scales are defined by vertical density gradients (e.g., mixed layer depth). For integral measurements, such as altimeter SSH, the US Navy uses an approach that requires additional information in the form of climatological relationships between SSH and temperature at depth and between temperature and salinity. These relationships are contained in the Modular Ocean Data Analysis System (MODAS; Fox et al., 2002), where the outcomes are synthetic profiles of temperature and salinity that are generated and assimilated when the observed altimeter SSH anomalies exceed the prescribed noise level of the altimeter.

Hurlburt et al. (2011) point out the positive impact that data assimilation has on model dynamics and the ability of a HYCOM/NCODA-based system to more accurately represent the Gulf Stream. They note an increase in the depth range of the deep western boundary currents (Figure 28 in Hurlburt et al., 2011) and an increase in the strength of the Atlantic meridional overturning circulation (Figure 29 in Hurlburt et al., 2011), when comparing a non-assimilative simulation with a data assimilative hindcast. The increased depth range of the deep currents generates more realistic abyssal currents along the continental slope. This result, in combination with vortex stretching and compression generated by the data-assimilative approximation to meanders in the Gulf Stream and related eddies in the upper ocean, yield an ocean model response that simulates the Gulf Stream-relevant abyssal current features seen in historical in situ observations.

THE HYCOM/NCODA RUNSTREAM

A single daily update cycle starts with the NCODA analysis at 18Z (Zulu, or Greenwich Mean Time) using the HYCOM forecast as a first guess and with the analysis window for altimeter data spanning ±36 hours, for profile data spanning –12 days to +12 hours, and for all other observations spanning ±12 hours. Then, HYCOM is run for 24 model hours with the NCODA incremental analysis update (Bloom et al., 1996) applied to the ocean model over the first six hours. Thus, at 00Z, HYCOM has fully assimilated all the observational data. Every day the system goes back 102 hours from the nowcast time because of late-arriving satellite altimeter data. The NCODA analysis and HYCOM hindcast cycle repeats itself four times up to the nowcast time (t = 0), and HYCOM continues to run in (non-assimilative) forecast mode out to t = 168 hours (one week). In subsequent versions of this global HYCOM/NCODA system, the daily four-day hindcast will be reduced to a one-day hindcast by using the First Guess at Appropriate Time capability within NCODA (for more details, see section 13.6 in Cummings and Smedstad, 2013).

EVALUATION OF NOWCAST/FORECAST SKILL

The evaluation of HYCOM/NCODA nowcast/forecast skill was performed on a yearlong data-assimilative hindcast spanning calendar year 2012. Two sets of 14-day forecasts were also integrated to examine medium-range forecast skill. Using the yearlong data-assimilative hindcast for the initial conditions, 14-day forecasts were run starting on the 1st, 8th, 15th, and 22nd of each month for a total of 48 forecasts. The first set of forecasts used "operational quality" forcing (i.e., the first five days used forecast NOGAPS atmospheric forcing), which was then blended toward climatological daily atmospheric forcing over a five-day period. Beyond 10 days, purely daily climatological NOGAPS forcing was applied. The second set uses NOGAPS daily analysis forcing for the entire 14-day "forecast" period. No oceanic data were assimilated during the forecasts.

PREDICTABILITY OF THE OCEANIC MESOSCALE

Mesoscale eddies are ubiquitous across the global ocean and impact phenomena ranging from ocean acoustic propagation to zooplankton production. Thus, it is essential that a prediction system

accurately represent these features of oceanic "weather." This is achieved mainly through assimilation of satellite altimeter data, but the ocean model itself must also be a good dynamical interpolator of this data stream. Eddies must be properly maintained and have accurate propagation speeds when they become unobserved between altimeter tracks.

In order to assess medium-range (14-day) forecast skill for the oceanic mesoscale, HYCOM/NCODA SSH forecasts are verified against the assimilative hindcast at 00Z, and root mean square error (RMSE) and anomaly correlation (AC) are used as the metrics. The RMSE is calculated as

$$RMSE(f, a) = \frac{1}{N-1}\sqrt{\Sigma(f-a)^2} \qquad (1)$$

where f represents the forecast and a represents the analysis (i.e., the data-assimilative hindcast). RMSE provides a measure of how well the SSH amplitude agrees between the data-assimilative hindcast and forecasts. AC provides a measure of the spatial similarity and is calculated as

$$AC(f, a) = \frac{\Sigma(f-\bar{c})(a-\bar{c})}{\sqrt{\Sigma(f-\bar{c})^2\,\Sigma(a-\bar{c})^2}} \qquad (2)$$

where $\bar{c}$ is the climatological mean that spans the 2012 hindcast period. Figure 2 shows forecast skill for the global ocean, the Gulf Stream and Kuroshio Extension, the South China Sea (a region with both chaotic eddy generation west of Luzon Strait and seasonally varying offshore flow), and the relatively shallow Yellow/Bohai Sea (a region where the ocean's response to atmospheric forcing is rapid and mainly deterministic).

The AC plots (Figure 2a–e) show three curves: forecasts of persistence (cyan), forecasts using operational quality forcing (red), and "forecasts" that use analysis quality forcing (green). Murphy

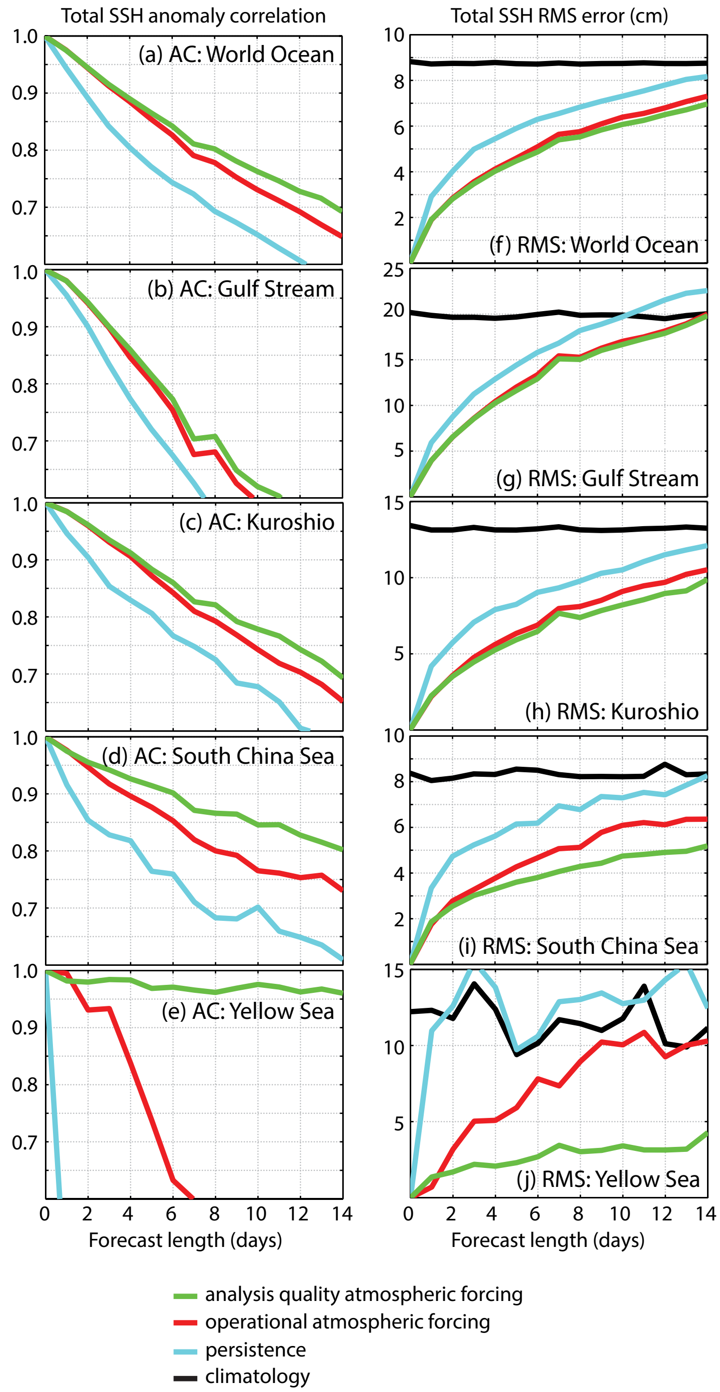

Figure 2. Verification of 14-day ocean forecasts, (a–e) median sea surface height (SSH) anomaly correlation (AC) and (f–j) median SSH root mean square error (RMSE) in centimeters vs. forecast length in days in comparison to the verifying HYbrid Coordinate Ocean Model (HYCOM) data-assimilative hindcast for (a,f) the global domain (45°S–45°N), (b,g) the Gulf Stream (76·°–40°W, 35°–45°N), (c,h) the Kuroshio Extension (120°–179°E, 20°–55°N), (d,i) the South China Sea (100°–122°E, 0°–27°N), and (e,j) the Yellow/Bohai Sea (118°–127°E, 30°–42°N). The curves depict median statistics over 48 14-day forecasts spanning calendar year 2012. The cyan curves verify forecasts of persistence, the red curves use operational quality atmospheric forcing that blends toward climatology after five days, and the green curves verify "forecasts" with analysis-quality atmospheric forcing for the duration. The black curve on the RMSE plots represents climatology (i.e., annual model mean SSH). Note the range of the y-axis varies among the RMSE panels. Navy Operational Global Atmospheric Prediction System (NOGAPS) atmospheric forcing was used in the hindcast and forecasts for this analysis.

and Epstein (1989) indicate AC > 0.6 represents useful model forecast skill. Additionally, the black curves on the RMSE plots (Figure 2f–j) represent verification of climatology (i.e., the system's annual mean). Anomaly correlation decreases and RMSE increases with forecast length. In addition, forecasts is a poor forecast. The atmospheric forcing has skill out to about six days in this region based on the ocean model response (red curve), but after three days it rapidly diverges from the analysis quality forcing (green) curve, which remains high for AC (low for RMSE) throughout the 14-day forecast period.

"[THE NAVY GLOBAL OPERATIONAL OCEAN PREDICTION] SYSTEM PROVIDES NOWCASTING AND FORECASTING OF OCEANIC "WEATHER," INCLUDING THREE DIMENSIONAL (3D) OCEAN TEMPERATURE, SALINITY, AND CURRENT STRUCTURE; SURFACE MIXED LAYER DEPTH; AND THE LOCATION OF MESOSCALE FEATURES SUCH AS EDDIES, MEANDERING CURRENTS, AND FRONTS."

using operational and analysis quality forcing are both more skillful than persistence. The spread between these curves is smallest for the Gulf Stream and Kuroshio Extension regions because of the chaotic nature of the mesoscale flow instabilities in these areas. Here, the predictive skill depends more on the quality of the initial state, the accuracy of the model dynamics, and the time scale of the flow instabilities than on the atmospheric forcing. However, even in these highly variable regions, the system shows forecast skill for the oceanic mesoscale out to ~10 days for the Gulf Stream and 14+ days for the Kuroshio. The Yellow/Bohai Sea is more sensitive to atmospheric forecast forcing than to the initial state; hence, the persistence forecast skill diminishes precipitously because persistence of the atmosphere

The next largest spread between the forecasts using operational and analysis quality forcing is for the South China Sea region. This is due to the relatively broad and shallow shelf areas in the southwest part of the domain and the rapidly transitioning nature of the monsoon winds.

GULF STREAM PATHWAY PREDICTABILITY

The inertial character of western boundary currents has historically been a challenging circulation characteristic for numerical ocean models to simulate and forecast. Assimilation of satellite altimeter data can constrain current pathways, but only up to the nowcast time. When the system runs in forecast mode, how well are the strength and position of the western boundary currents maintained? This is highlighted for the Gulf Stream region in Figure 3, which shows speed at ~ 25 m depth from the 2012 data-assimilative hindcast, the forecasts, and the difference between the two, all of which are averaged over the 48 dates that end the 14-day forecast. The pathway of the 14-day forecast Gulf Stream at separation from the coast at Cape Hatteras is more zonally oriented and south of that found in the data-assimilative hindcast out to about 64°W. This is a common trait of non-assimilative numerical ocean models at this horizontal resolution, as noted by Hurlburt et al. (2011). Nonetheless, the overall forecast pathway and current speeds are maintained quite consistently with speed differences generally smaller than ±10 cm s^{-1} across most of this domain. This is similarly true for the Kuroshio, the mid-latitude western boundary current in the North Pacific.

SUBSURFACE TEMPERATURE STRUCTURE

Accurate forecasts of subsurface temperature, salinity, and velocity structure are a first-order requirement for ocean prediction systems. The vertical distributions of temperature, and to a lesser extent salinity, determine sound speed properties. Near-surface stratification, surface mixed layer depth, and thermocline gradient also play important roles in sound propagation. Therefore, the predictability of ocean temperature and salinity is vital to accurate simulation of the underwater acoustical environment—a key Navy concern.

A temperature versus depth error analysis as a function of forecast length is performed for the 2012 data-assimilative hindcast using observed profile data from the GODAE server (http://usgodae.org). For a given

observation, the system is sampled at the nearest model grid point and interpolated in the vertical to the observation depths. The analyses are broken down by regions and performed for the upper 500 m of the water column (the number of profiles available for validation drops off significantly below this depth). The statistical metrics are mean error (ME) (bias) and RMSE. The first depth used in the analysis is at 8 m.

Figure 4 highlights the temperature error in HYCOM/NCODA validated against unassimilated profile data, and the spatial plot (a) shows RMSE averaged over the top 500 m. Not unexpectedly, highest RMSE is in the regions of the highly energetic and eddying western boundary currents (Gulf Stream, Kuroshio, Agulhas Retroflection, and Brazil-Malvinas) and along the Antarctic Circumpolar Current. However, depth-averaged RMSE is less than 0.5°C over much of the global ocean. The spatial distribution and amplitude of the error is similar to the French Mercator system, although the latter was validated against assimilated profiles (see Figure 6 in Lellouche et al., 2013).

The bottom row panels (b–d) show ME and RMSE as a function of forecast length for the three boxed regions in (a) with the black, cyan, and red curves showing the statistics for the 6-to-24-hour, seven-day, and 14-day forecasts, respectively. Overall, HYCOM has a small cold bias (< 0.25°C) at the first forecast time. Only the Atlantic region shows any marked increases in bias as a function of forecast length, and those, too, are modest. RMSE peaks between ~ 50–200 m (i.e., the depth range of high variability associated with the mixed layer and thermocline), with the highest error in the Indian Ocean region. RMSE increases by

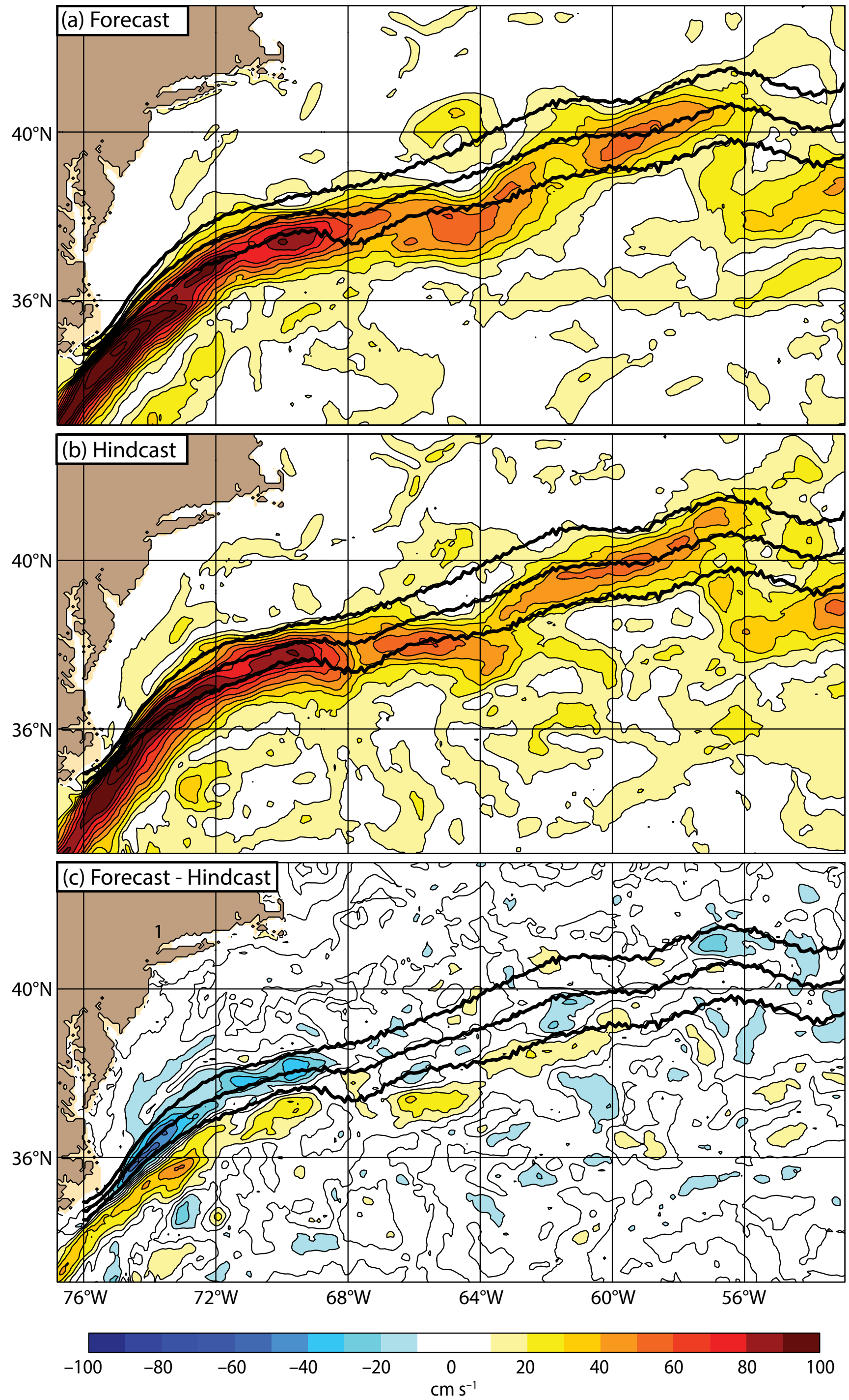

Figure 3. HYCOM/NCODA (HYbrid Coordinate Ocean Model/Navy Coupled Ocean Data Assimilation) speed (cm s^{-1}) for layer 6 (~ 25 m depth) in the Gulf Stream region for (a) the forecasts using operational quality forcing, (b) the data-assimilative hindcast, and (c) the forecast minus the hindcast. All are averaged over the 48 dates that end a 14-day forecast. The contour interval is 10 cm s^{-1}. The superimposed bold black lines represent the 15-year mean Gulf Stream infrared northwall pathway ±1 standard deviation (Peter Cornillon, University of Rhode Island and Ziv Sirkes, University of Southern Mississippi, *pers. comm.*, January 22, 1997). NOGAPS atmospheric forcing was used in the hindcast and forecasts for this analysis.

approximately 13% (22%) for the seven-day (14-day) forecasts averaged over the regions shown.

ARCTIC SEA ICE FORECASTING

Preller et al. (2002) discuss Navy sea ice prediction systems and describe the Polar Ice Prediction System (PIPS) that began producing operational Arctic ice forecasts in July 1996. PIPS continued in that role until 2011 when it was replaced by the Arctic Cap Nowcast/Forecast System (ACNFS). Its model components are the Community Ice CodE (CICE; Hunke and Lipscomb, 2008), developed at Los Alamos National Laboratories, and HYCOM for the underlying ocean. CICE has more sophisticated physics than the "energy-loan" ice model used in the global system, and improvements over earlier ice models include multiple ice thickness layers, multiple snow layers and new ice ridging parameterizations. The ocean and ice models are fully two-way coupled via the Earth System Modeling Framework (Hill et al., 2004), with fields passed between them every hour. The domain is identical to the global HYCOM/NCODA system north of 40°N, with the latter providing the ocean boundary conditions at this latitude. Its horizontal resolution is ~ 3.5 km near the North Pole. ACNFS uses the same atmospheric forcing as the global system. CICE is updated at 18Z by direct insertion of an NCODA analysis of ice concentration derived from satellite Special Sensor Microwave Imager Sounder data. Then, ACNFS

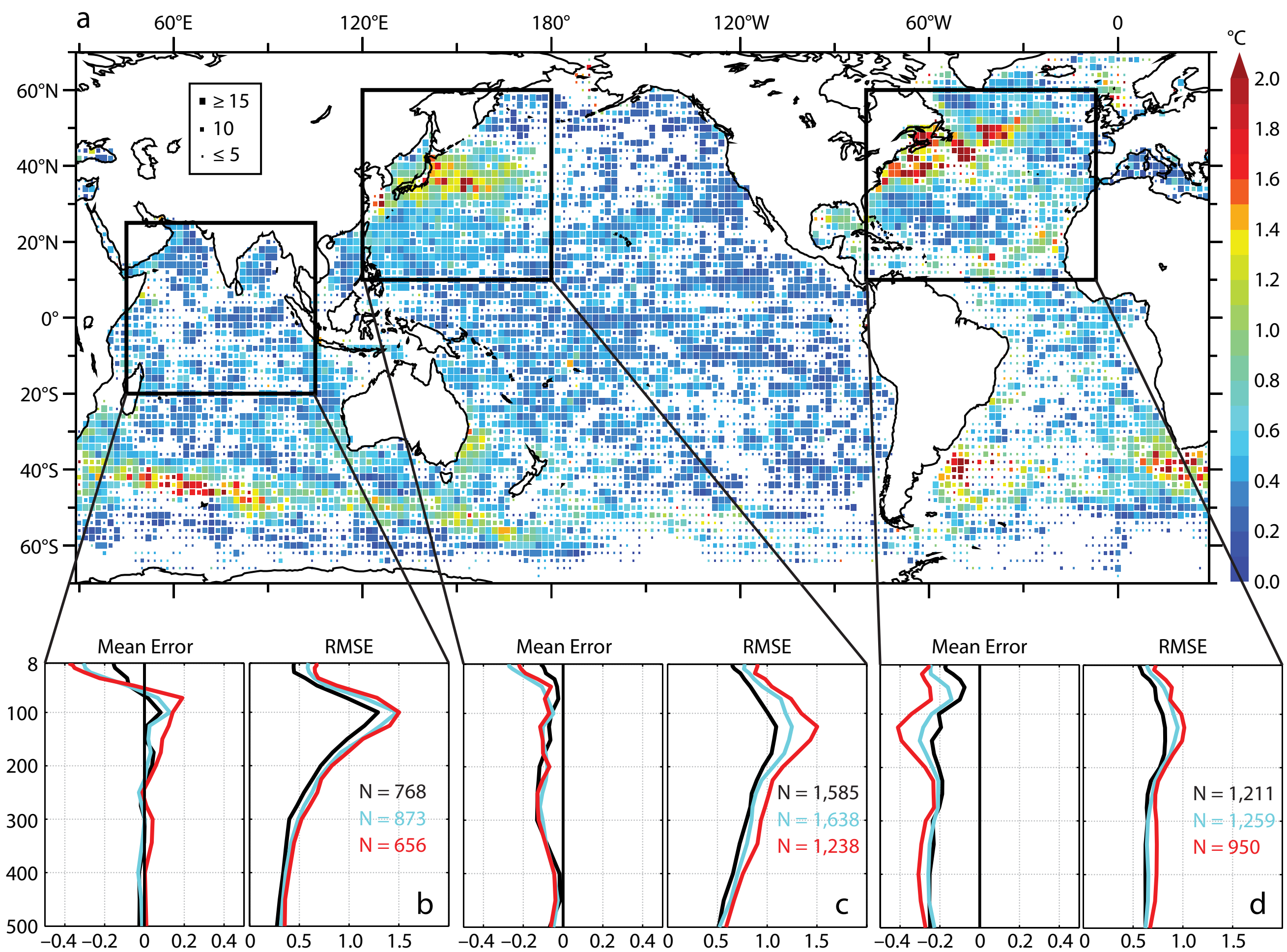

Figure 4. Temperature (°C) vs. depth error analysis against unassimilated profiles during the data-assimilative hindcast spanning 2012. (a) RMSE in 2° bins averaged over the top 500 m at 00Z. Approximately 100,000 profiles went into the analysis, and the number of profiles in each bin is denoted by the legend in Asia. (b–d) Mean error and RMSE as a function of depth and forecast length for the three regions outlined in (a). The black curves are for the 6-to-24-hour short-term forecast, the cyan curves for the seven-day forecast, and the red curves for the 14-day forecast. The number of temperature profiles used in each analysis region is denoted by N = XXX. Model-data differences greater than three standard deviations are excluded from the analysis. NOGAPS atmospheric forcing was used in the hindcast and forecasts for this analysis.

provides seven-day forecasts of ice concentration, thickness, drift, and many other fields to the US National Ice Center (NIC). An example of ice concentration at the winter ice maximum and summer ice minimum is shown in Figure 5. The summertime NIC-ACNFS ice edge discrepancy is due in part to a known problem with passive microwave satellite imagery underestimating ice due to surface melt ponds. To correct this, research is currently underway to assimilate the more accurate Multisensor Analyzed Sea Ice Extent product created by the NIC and distributed by the National Snow and Ice Data Center. Posey et al. (2010) validated this interim ice prediction system, which will be replaced by the global coupled HYCOM/CICE/NCODA system in the near future. Graphical ACNFS output can be found at http://www7320.nrlssc.navy.mil/hycomARC.

Maritime operations in the polar latitudes rely on accurate prediction of the ice edge. The accuracy of these predictions is illustrated in Figure 6, which shows RMSE versus time and forecast length for ACNFS ice edge against an independent analysis from the NIC. For the period July 2010 to June 2011, approximately 100 five-day forecasts were integrated and ice edge location error was computed as a function of forecast length. Ice edge location error is higher during the summer months in part due to the passive microwave imagery problem noted above. During the beginning of the rapid ice growth season (October to December), ACNFS forecasts slower than observed ice growth, especially in the marginal seas, leading to higher error. However, during the winter months, error does not grow much as forecast length increases. Averaged over the entire year, the six-hour forecast RMSE is 79 km, the 78-hour forecast RMSE is 92 km, and the 126-hour forecast RMSE is 104 km.

FUTURE SYSTEM DEVELOPMENT

Over the coming years, new capabilities will be added to improve the global prediction system. The first phase will be transitioned from research and development to NAVOCEANO for operational implementation in mid-2014 and includes: (1) an increase in HYCOM's vertical resolution from 32 to 41 layers, with the nine new layers added near the surface to improve upper ocean prediction, (2) an improved method for projecting altimeter-based sea surface anomaly information into the ocean interior by replacing MODAS synthetics with Improved Synthetic Ocean Profiles (Helber et al., 2013), and (3) two-way coupled HYCOM/CICE, as in ACNFS, which will provide Southern Hemisphere ice forecasts as well.

By 2016, plans for HYCOM include a horizontal resolution increase to 0.04° (~ 3.5 km at mid-latitudes) and the addition of tidal forcing. This system will provide boundary conditions for even higher resolution coastal models and serve as the backbone of a globally relocatable ocean nowcast/forecast capability that will address the need for littoral or deepwater support anywhere in the world, without the need for most intermediate regional models. It will allow direct nesting of a relocatable model with 1 km resolution in coastal and open

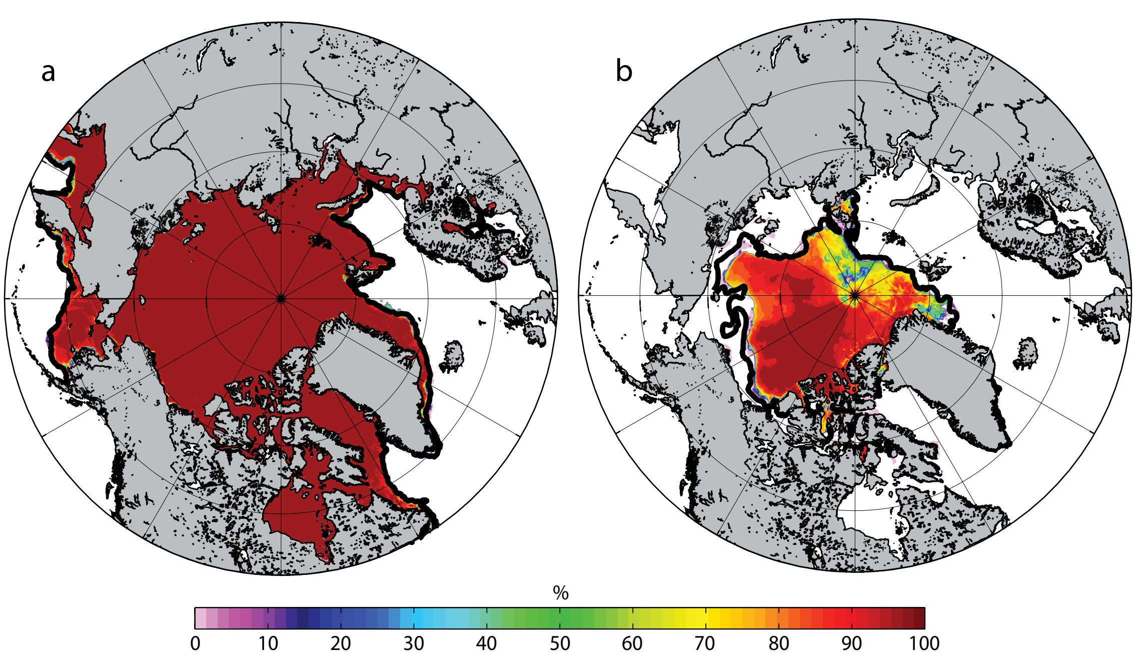

Figure 5. Ice concentration (%) for (a) March 9, 2013, and (b) September 9, 2013, from the Arctic Cap Nowcast/Forecast System run daily at NAVOCEANO. Both panels are at 00Z and are six hours after the NCODA ice analysis has been directly inserted into CICE (Community Ice CodE). The thick black line is an independent ice edge analysis from the National Ice Center. The atmospheric forcing came from NAVGEM.

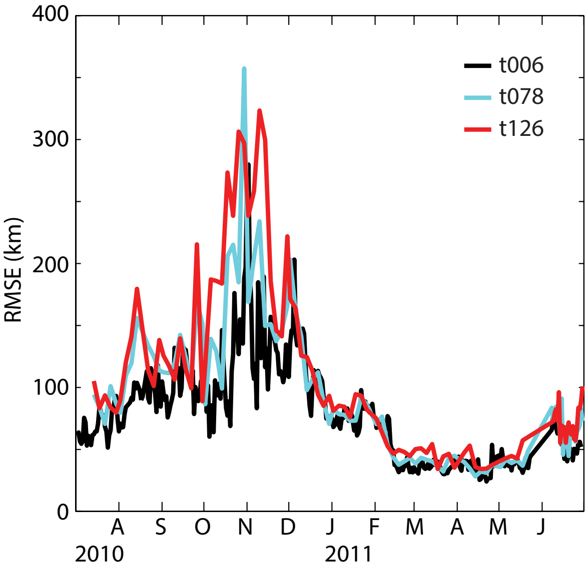

Figure 6. Root mean square error (km) versus time over the entire Arctic region for ACNFS (Arctic Cap Nowcast/Forecast System) ice edge (defined as 5% ice concentration) against the independent ice edge analysis from the National Ice Center. All comparisons are performed at 00Z. Because the NCODA ice analysis is performed at 18Z and directly inserted in CICE, the black curve is the 6-hour forecast, the cyan curve is the 78-hour forecast, and the red curve is the 126-hour forecast. NOGAPS atmospheric forcing was used in the forecasts for this analysis.

areas. Arbic et al. (2012, and references therein) describe the efforts to implement tidal forcing in global HYCOM and demonstrate that simulated internal tides compare well with satellite-based estimates. This new capability will allow nested coastal models to include internal tides at their open boundaries.

Lastly, developmental efforts are underway to build a data-assimilative, fully coupled global atmosphere (NAVGEM), ocean (HYCOM), ice (CICE), wave (WAVEWATCH III™), land (NAVGEM-Land Surface Model), and aerosol (Navy Aerosol Analysis and Prediction System) system as part of the Earth System Prediction Capability (Eleuterio and Sandgathe, 2012; Metzger et al., 2014). A demonstration of the first operational version of this system is presently scheduled for 2018.

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